# Automated Monitoring and Analysis of Circuit Breaker Operation

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*Abstract*—This paper describes a solution for automated analysis of circuit breaker operation. The analysis is based on a record of waveforms taken from the circuit breaker control circuit by using a portable recorder and manually forcing an operation of the breaker. This solution was driven by a need to perform the analysis in a more timely and consistent manner than what is available with existing technology. The solution is implemented using advanced wavelet transforms for waveform feature extraction and an expert system for decision making. A web-based database solution for storing and retrieving both the field-recorded and processed data is also implemented. The software is developed in two versions: for field (substation) as well as off-line (office) applications.

*Index Terms*—Circuit breaker testing, expert systems maintenance, monitoring, signal processing, wavelet transforms.

## I. INTRODUCTION

▼ IRCUIT BREAKERs (CBs) represent one of the most crit-, ical power apparatus in the power system. They are used to change topology of the power system to accommodate various configurations in routing the load. CBs are also used to isolate faulted parts of the system as a part of the protective relaying operation. Due to such a critical role, CBs need to be ready to operate at all times and any disruption in their operation may have costly consequences. However, preventive maintenance and testing intervals can be many years apart. To prevent CB miss-operation, the CBs are inspected and monitored on regular basis. In performing such a task, one obstacle is quite obvious: an average size utility may have thousands of CBs in service. The sheer number of CBs makes it almost impossible to perform the inspection and monitoring with sufficient frequency. The cycle may be as long as a year, which leaves room for a number of early signs of deteriorating performance to go undetected.

A typical existing CB inspection practice is to use portable recording sets that are carried from substation to substation and connected to the CB manually by the maintenance staff

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[1]. Once the recording set is connected, the CB is forced into operation and a record of signals from the control circuitry is taken. The maintenance crew visually analyzes the record on the spot for abnormalities that appear in the waveforms, and if deemed necessary, CB corrective maintenance is initiated [2]. This process is rather tedious and subject to an interpretation and particular expertise of the individuals involved [3]. As a result, the post-inspection actions may vary from a crew to a crew and inconsistent CB corrective maintenance may result in different levels of readiness of CBs even after inspection is performed.

The two mentioned problems, namely the large number of CBs causing the long intervals between inspections and the diagnosis inconsistency causing uneven maintenance practices, led the utilities to consider more efficient and consistent means of monitoring and analyzing CB operations [4]. This paper presents a solution that is based on the use of advanced signal processing and expert system concepts [5]-[7]. The implementation is aimed at developing a set of software tools for automated analysis of CB conditions. The system collects samples of signals obtained from CB control circuitry, extracts the required signal features and passes them to an expert system for reaching the final conclusions. Since the whole data analysis process is automated, the time required to perform the diagnosis and maintenance may be significantly reduced. At the same time, since the rules for the analysis are hard coded, the diagnosis is very consistent. To facilitate the storage and retrieval of both the raw data and results, web-based database access techniques are also implemented [8]. The main features of a system developed for CenterPoint Energy in Houston are described in this paper.

The paper starts with a discussion of the background, and then continues with a presentation of the solution for waveform feature extraction, expert system reasoning and advanced user interfacing. The system test results and conclusions are given at the end.

#### II. BACKGROUND

The monitoring focus is a CB control circuit. In existing practice, recording of signals from the control circuit is performed by using a portable recording device, which is moved from one CB to another and reconnected each time when analyzing a different CB [1].

Fig. 1 displays a simplified version of a commonly used control circuit representation called the X-Y relay scheme. The schematic can be divided into two sections. The section that

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TABLE I Representative Signal Waveforms



Fig. 1. CB control circuit.

controls the opening sequence includes the branch that contains the trip coil (TC) and CB (52a) auxiliary contact. The section that controls the closing sequence includes all the remaining branches in the circuit diagram. Table I shows how various signals monitored in the control circuit change throughout opening and closing operations.

Opening or closing operation of CB begins with an initiate signal being sent to the control circuit from an operator in the control house, a protection relay, or a control device. The auxiliary contacts and control relays are designed to allow the initiate signal to connect to the trip or close coil (labeled TC & CC respectively) in Fig. 1. The initiate signal energizes the coil that in turn creates a coil current as shown in Table I. Being energized, the armature of the coil moves up to release the latch, and triggers the movement of the operating mechanism. At the same time, the coil currents in Table I tend to saturate as the coil tries to release the latch, and a small dip after the saturation indicates when the mechanism is in motion. The stored energy is used to move all the mechanical parts within the CB and open or close the main interrupting contacts. As a consequence, CB auxiliary (52a) and (52b) contacts change state and phase currents also break or make according to the type of operation. Table II gives a general description of an operation process and makes a

 TABLE
 II

 SEQUENCE OF CIRCUIT BREAKER TC/CC OPERATION



correlation among the control circuit changes, CB mechanism actions and related waveform indications.

Signals collected from the control circuit contain information that can be used to evaluate the condition of different sub-assemblies of CB. The transition of the initiate signal starts the operation sequence. The time difference between the transitions of auxiliary contacts (52a and 52b) indicates the relative speed of CB operation. The time difference between the coil current energizing and de-energizing measures overall time of the latch and the mechanism movement. Usually abnormal behavior of signal waveforms implies an existing problem or a developing failure. For example, delayed transition of phase current indicates a slow operation; the excessive noise during the contact transition indicates a dirty auxiliary contact; the excessive voltage drop of DC voltage indicates a battery problem, etc. [3]. In summary,

SIGNAL	OBSERVED ABNORMALITIES	SIGNAL	
TYPE		PARAMETERS	
Trip or Close	Signal resets prematurely	T1	
Initiate	Dropout during operation	DRP	
	Abnormal noise on contacts	NOI	
"o" or "h"	Contacts bounce	BOU	
a or b	Transition time is increased	T5 (B), T6 (A)	
Contacts	Transition time is reduced	T5 (B), T6 (A)	
	Dropout during operation	DIP	
	Dip delayed	T3	
	Delayed drop-off or no drop-off	T4	
	Distorted (Choppy) waveform	NOI	
Trip or Close	Current flat	T2, T4	
Coil Currents	Current pick-up delayed	T2	
	Current pick-up premature	T2	
	Coil current has excessive	SUP	
	suppression when de-energizing		
X & Y Coils	Late or no activation	T8 (X), T10 (Y)	
	Late or no deactivation	T10 (X Coil)	
	Premature deactivation	T10 (X Coil)	
	Dropout during operation	DRP	
Phase	No drop or no rise	T7	
Currents	Re-strike	RES	
DC Voltages	Voltage drops below threshold	DIP	
	Oscillations on the waveform	RIP	
	Noise (distortion)	DIS	
	Spike	SPI	

TABLE III WAVEFORM ABNORMALITIES AND SIGNAL PARAMETERS

two major categories of information can be identified from the control circuit signals. The first is the sequence (or the coordination) of the transition times of different signals; the second are the abnormalities of each individual signal that are unrelated to time.

In order to extract the features from the waveform and evaluate the overall operation, signal processing and expert system module are designed to achieve the two tasks mentioned above automatically.

#### **III. SIGNAL PROCESSING**

#### A. Feature Definition

To extract relevant information from the signals, features reflecting the waveform abnormalities are defined, and signal parameters describing the features quantitatively are specified. Signal parameters are classified into two groups: a.) Events time parameters designated with T1–T10 describing the ten features, and b.) Waveform distortion parameters used for describing noise (NOI), ripple (RIP), voltage drop (DIP), etc. [4]. A summary of the signal parameters and features is provided in Table III. Events refer to a signal transition or an unusual change in the waveform profile. A maximum of ten events have been identified. Not all of these events will take place in a CB operation. For example, events related to X and Y coil will only appear in a close operation for certain types of CB. The first seven events are expected to show up in every data record.

Take the Trip Coil current as an example. A normal Trip Coil (TC) current makes a gradual transition to a nonzero value immediately after the Trip Initiate is activated. TC current continues to increase at a steady rate until it reaches a small dip



Fig. 2. Actual trip current waveform and parameters.



Fig. 3. Three level feature extraction.

before leveling off at the top of the waveform as shown in Fig. 2. The dip corresponds to "the point where the trip coil has released the trip linkage to allow the CB mechanism to operate" [3]. Then, the TC current may rise slightly or remain flat at its maximum value until it starts dropping down. The TC current signal should be fairly smooth except for the dip at the point T3.

For a Trip Coil current signal, five parameters illustrated in Fig. 2 are selected to represent its features. The Trip Coil current signals exhibit several different types of abnormalities.

One type of abnormality found in the coil current is a delayed transition to a nonzero value. If the pick up of Trip Coil current is delayed, it will be represented by the parameter T2. Other parameters are defined in a similar way to characterize certain features in the signal.

# B. Feature Extraction

The local information (e.g., an event) mingled with global features (e.g., ripples) makes the wavelet decomposition and reconstruction filter banks a perfect feature extractor for this data pre-processing application [5]. During the pre-processing, it is necessary to perform a three-level feature extraction: de-noising, splitting, and signal parameter calculation.

De-noising is used to suppress the excessive instrumentation noise and reveals the features that may otherwise be distorted by the noise. Soft thresholding is used in de-noising to preserve the desired signal features. In the de-noising example shown in Fig. 3, the reconstructed trip coil current beneath the noisy appearance still contains the time features.

The Splitting process is expected to separate the features and thus facilitate calculation of the signal parameters for individual



Fig. 4. Layers of analysis.

features. In the splitting example shown in Fig. 3, trip coil current is decomposed into six levels using "db1" [5]. The detailed signal at level 4 is used to calculate the dip feature.

Signal parameters are calculated after de-noising and splitting process. The event location example in Fig. 3 shows how to detect the dip event in the trip coil current. The sixth level current approximation is in the shape of steps. The fourth level detail preserves all the event information such as the beginning time, dip time, and de-energizing time of the coil current. Making a correlation between the approximation and detail signal helps to locate the dip time within the most significant stair.

#### **IV. EXPERT SYSTEM**

#### A. Architecture

The overall design consists of a signal-processing module that supplies signal parameters, the user interface that supplies settings, and the expert system that returns an event report. The signal parameters and settings represent the facts and the event report represents the expertise provided by the expert system [6]. Initially, the knowledge base was designed and developed in the CLIPS expert system shell that contains a command interface and inference engine. Later, the CLIPS shell is encapsulated into a dynamically linked library (DLL) [7].

The knowledge base contains a set of basic and complex rules that analyze the signal parameters against the expert system settings to produce the output report (Fig. 4). Basic rules are fired directly by signal parameters. They are used to make sure that all the extracted parameters are within their corresponding tolerances. If a parameter is outside a tolerance, then the rule that checks the parameter becomes activated. The activated rules from the first layer of analysis provide some preliminary results about the CB condition.

Complex rules can be fired by signal parameters acting either directly or indirectly through other rules. They are used to analyze the interrelationship between all of the activated basic rules. Based on which rules were activated, the expert system tries to come to a conclusion about the overall performance of CB. A certain combination of basic rules may indicate a particular problem whereas a different combination would indicate

TABLE IVDESCRIPTION OF RULE 28

Rule 28: TC Drop I	Delayed/No Drop
The rule fires in	The TC current remains at a non-zero value longer
case when	than expected after its transition from zero.
Parameter(s)	The actual time of the TC Drop (T4).
Threshold(s)	The expected time of the TC Drop.
Rule Scope	Specific to opening
Output Statement	This is a very slow or stuck CB.

another problem. All together 99 rules have been defined so far as given in Table V.

The definition of a rule includes a description of the circumstance (with illustration) that will fire (activate) the rule, a list of related signal parameters, thresholds, limited scope of the rule and an output statement. A simple rule definition for "coil current" is given in Table IV as an example. This example rule is to verify that the trip coil (TC) current drops from a sustained value to the zero value within expected time.

## B. Temporal Reasoning Process

Activation of a rule usually triggers the firing of more complex rules in a way similar to a chain reaction. Fig. 5 illustrates a group of expert system rules and the temporal reasoning process executed from the signal parameter extraction to the complex rule firing. The rectangle represents extraction of the signal parameter T5 and T6. The ovals right below represent the basic rules that can be fired by the signal parameters. The ovals named R68 and R71 represent the complex rules that can be fired by signal parameters, basic rules or complex rules.

What is shown in Fig. 5 is only one possible combination of rules that may finally reach the conclusion of a "binding on "b" contact" condition. Basic rules 24 and 25 are checked to verify that the "b" contact signal does not make premature or delayed transition to its sustained value. Fig. 5 uses shadings to show that these two rules are checked by the reasoning, but not fired. In parallel, rules 18 and 19 are designed to verify the same conditions for the "a" contact as that for the "b" contact. Rule 18 in this case is fired because the "a" contact voltage makes transition to its sustained value well before the expected time instant, which equals to a sum of the set value and  $\pm$  tolerance, as shown in Fig. 6.

Complex rule 68 is created to verify the velocity of the CB mechanism movement. R68 will be fired if the time difference between "a" and "b" contact transitions is increased. Given the combination depicted by the shaded and nonshaded ovals (rules) in Fig. 5, R68 is fired. Table VI gives description of the complex rule 71 defined in a CLIPS rule file in Fig. 7.

In summary, contrasting with the variant judgments of different experts, the expert system software provides a generic and consistent solution. Empirical information is stored in form of rules and settings introduced above, and consistent analysis is achieved through temporal reasoning based on rules, settings, and inference engine. This is the reason why the automated analysis systems work in a different way than the individual experts do.

The output of the expert system is a concise event report that summarizes the results of the analysis. One of the sections in the

TABLE V SUMMARY OF EXPERT SYSTEM RULES

R1Breaker Opens	R38
R2 Breaker Closes	R39
R3 TI Resets Prematurely	R40
R4 TI Drops Out	R41
R5 CI Resets Prematurely	R42
R6CI Drops Out	R43
R/Control DC Voltage Unstable	R44
Recontrol DC Voltage Distorted	R45
R10 Control DC Voltage Snike	R40
R11 Vard DC Voltage Unstable	R48
R12 Yard DC Voltage Rippled	R49
R13 Yard DC Voltage Distorted	R50
R14 Yard DC Voltage Spike	[Pole
R15 "a" Contact Unstable	R51
R16 "a" Contact Noisy	R52
R17 "a" Contact Bounce	R53
R18 "a" Contact Premature	R54
R19 "a" Contact Delayed	R55
R20 "a" Contact Flat	Dela
R21 "b" Contact Unstable	R36
R22 "D" Contact Noisy	Pren D57
R23 D Contact Bounce	R58
R24 0 Contact Tremature R25 "b" Contact Delayed	R50
R25 "b" Contact Elat	R60
R20 TC Current Flat	Pren
R28 TC Current No Drop	R61
R29 TC Current Distorted	R62
R30 TC Current Dip Delayed	Dela
R31 TC Pickup Delayed	R63
R32 TC Pickup Premature	R64
R33 TC Bad Suppression	R65
R34 CC Current Flat	R66
R35 CC Current No Drop	R67
R36 CC Current Distorted	R68
R37 CC Current Dip Delayed	K09
Contact	
R71 Effect of Binding on "b"	R88
Contact	Pren
R72 Sequence A-B Violated	State
R73 Friction in Trip Assembly	R89
R74 Close Coil Armature-Latch	Repa
Friction	R90
R75 Travel Time Decreased	Dela
R76 Travel Time Increased	R91
R77 Trip Latch Maladjustment	Pren
R78 Close Assembly	State
Maladjustment	R92
R/9 TI/CI Output Statement R80 Control/Vard Output	
Statement	Ren
R81 "a"/"b" Contact Output	Repa
Statement	Rena
R82 TC/CC Flat – Repair	R95
Statement	Repa
R83 TC/CC No Drop – Repair	R96
Statement	Repa
R84 TC/CC Distorted – Repair	R97
Statement	State
R85 TC/CC Dip Delayed –	R98
Repair Statement	State
Roo IC/CC Pickup Premature	куу
- Repair Statement	

R38 CC Pickup Delayed R39 CC Pickup Premature R40 CC Bad Suppression R41 Phase A: No Rise R42 Phase A: No Drop R43 Phase A: Delayed R44 Phase B: No Rise Phase B: No Drop R45 Phase B: Delayed R46 Phase C: No Rise R47 R48 Phase C: No Drop Phase C: Delayed R49 R50 Phase Time Violation Pole Alignment] R51 Breaker Re-strike R52 X Coil No Activation R53 X Coil Activation Delayed R54 X Coil No Deactivation R55 X Coil Deactivation Delayed R56 X Coil Deactivation Premature R57 X Coil Drops Out R58 Y Coil No Activation R59 Y Coil Activation Delayed R60 Y Coil Activation Premature R61 Y Coil No Deactivation R62 Y Coil Deactivation Delayed R63 Y Coil Drops Out R64 Breaker Opening Slow R65 Breaker Closing Slow R66 Stuck Breaker (Opening) Stuck Breaker (Closing) R67 R68 Velocity Decreased Velocity Increased R69 R87 Phase Currents No Rise/No Drop – Repair Statement R88 X/Y Coil Activation Premature/Delayed - Repair Statement R89 X Coil No Deactivation -Repair Statement R90 X Coil Deactivation Delayed – Repair Statement R91 X/Y Coil Premature/Delayed - Repair Statement R92 Y Coil No Deactivation -Repair Statement R93 Velocity Decreased -Repair Statement R94 Velocity Increased – Repair Statement R95 Travel Time Decreased -Repair Statement R96 Travel Time Increased – Repair Statement R97 Effect of Binding – Repair Statement R98 Breaker Re-strike – Repair Statement



Fig. 5. Analysis including complex rule.

Rule 68 fired in an "Open" Operation



Fig. 6. Rule 68 fired in an CB "Open" operation.

;----Effect of Binding on "b" Contact----

(defrule R71 (declare (salience -900)) (initial-fact) (not (R71\_fired)) (closing) (b\_contact ?TIM ? ? ?) (set\_b\_contact ?SETTIM ?TOL ? ?) (R68\_fired) (test (< ?TIM (+ ?SETTIM ?TOL))) (test (> ?TIM (- ?SETTIM ?TOL))) =>

(assert (R71\_fired)) (printout t crlf " R71: Effect of mechanism binding (bearing friction) on 'B' contact!" crlf) (printout outFile crlf " R71: Effect of mechanism binding (bearing friction) on 'B' contact!" crlf)

)

Fig. 7. Expert system rule for effect of binding on "b" contact.

and name for each rule. The rule names serve a dual purpose in that they briefly show the reasoning behind the analysis and then they inform the user about the preliminary and final results.

### V. SYSTEM SOLUTION AND USER INTERFACE

The system architecture is split between two locations: the substation where data are collected during CB data recording and central repository where data from all monitored CBs are gathered. Software residing on a laptop is utilized for on-site

report is a list of all the rules that were fired with the identifier

Default Repair Statement

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Fig. 8. Screenshot of the analysis module main window.

TABLE VI DESCRIPTION OF RULE 71

Rule 71: Effect of I	Mechanism Binding (Bearing Friction) on "b" Contact		
The rule fires in	The velocity is decreased AND		
case when	The response time of "b" contact is normal		
Parameter(s)	The actual time of the response time of "b" contact.		
Threshold(s)	The expected time of the response time of "b"		
	contact.		
Rule Scope	Specific to closing		
Output Statement	An auxiliary contact may be broken or the		
	mechanism may be binding.		

analysis performed in a substation. It gives instant results about CB performances and directions how to address detected problems. Software residing on the server in the central repository is used for off-site analysis. Records and results are archived to the database and made available to the users within the company through the web application.

## A. User Interface for Analysis Module

Analysis module is part of both the client and server solution. A screenshot of the analysis module main window is displayed in Fig. 8. The "Waveform window" in which all input signals are displayed is denoted with (1). Both currents and voltages are displayed in the same window, one under the other, enabling comparison of the CB behavior at same time instances. Up to 5 different records can be selected for overlaying in the waveform window, together with the reference cases for a particular CB operation. Different records can be shown in the user selected and customized colors emphasizing waveforms and events of a particular record. "Signal parameters window", marked with (2), displays signal names and values of extracted parameters. Tag (3) denotes the "Status window" which is used for displaying progress of the processing. This window displays error message if analysis fails or if the user interrupts processing. When processing of a single record is completed, analysis report is displayed within this window. By scrolling it, user can view the list of expert system rules fired, reflecting relations between extracted parameters, tolerances, hard coded rules, and CB performance. At the end, maintenance and repair information customized for each type of CB is given, directing operators how to handle detected CB problems.

Fig. 9 displays the dialog for viewing and changing Expert System settings. Dialog for changing Signal Processing settings has similar user interface. Setting consists of a set value and a tolerance. The set value represents the expected normal value for

Breaker selection		Coil Current		DCVoltage
XY coil		Phase currents		Contact
	Ph	iase A		Phase B
	open	close -	[°	pen close
RISETIME	1.00	0.084	- F	.000 0.084
TOL1	0.000	0.010	0.	000 0.010
DROPTIME	0.024	-1.00	0 0.	024 -1.000
TOL2	0.008	0.000		008 0.000
		open	close	7
RISETIME		-1.000	0.084	Phase C
	TOL1	0.000	0.010	
DROF	TIME	0.024	-1.000	BRKPERIOD
	TOL2	0.008	0.000	0.015
Edit	1	Save	Defau	ilt Ölear

Fig. 9. Screenshot of the Expert System settings dialog.

a parameter and the tolerance specifies the degree of freedom that the parameter is allowed to deviate and still be considered normal. There are also settings that specify a maximum limit that the parameter must be under, to be considered normal. Both Expert System and Signal Processing settings dialogs are tabbed, where each tab corresponds to alike signals.

With the feature allowing the change of settings one can make appropriate adjustments for a specific manufacturer's circuit breaker type. The 99 rules mentioned in Table V can be expanded for differences in circuit breaker mechanism that require new rules.

The user can select CB manufacturer and CB type and then view, edit, save or delete settings pertaining to that CB type. There are different setting values as well as tolerances for the "open" and "close" CB operation.

## B. User Interface for Web Application

The web application enables the users connected to the company intranet to access data stored in the database using web browser software. The web application is implemented using ASP.NET Microsoft technology based on server processing [8].

The web application user interface provides support for the following functions:

- authorizing and authenticating the users;
- searching the data records and reports in a basic (default) mode;
- searching the data records and reports in an advanced mode;
- displaying data signal waveforms and analysis reports;
- presenting the system and substation statistics using graphics;
- displaying Signal Processing and Expert System settings;

TABLE VII Criteria for Advanced Search of Data Records

CRITERIA	EXAMPLE
Substation Name	DOWNTOWN
Date	(1/1/2002) or from (1/1/2002) up to (6/24/2002)
Breaker Manufacturer	General Electric
Breaker Type	FK-339-250
Classification	(good) or (bad)
SAP ID	653285213
Device ID	20B0
Operation	(open) or (close)
Record name assigned based on the IEEE naming convention [9]	020212,120000777,-5D,THW- ,20B0,CNP,WH,R3,1234567,C

- classifying the data records and analysis reports in a remote and manual mode;
- transferring files of data records between the server and workstations connected to the company intranet and vice versa;
- maintaining the remote user accounts;
- exporting search results to the spreadsheet.

The most important feature for the user interface of the web application is support for efficient and fast search of various data records stored in the database. Table VII lists the search criteria with examples of possible values.

# VI. SYSTEM TESTING AND PERFORMANCE EVALUATION

# A. System Testing

There are two steps in the testing procedure. The first step is to verify the functioning of signal processing and expert system modules. One CB is taken out of service and test data are intentionally created to contain desired features and meet specific rules. The second step is to define settings for different types of CBs. Test data used in this step is collected from in-service CBs from different substations.

It was found that waveform profiles are similar and the transition time defined by time parameters are close for the same type of CB. To define settings, manufacturer manuals and personal expertise are good references. For example, the settings of phase current break time T7 can be defined from referencing the CB interrupting time in the manufacturer manuals. Another method is to use probabilistic models to obtain the estimate and deviation of signal parameters and define a set value and tolerance based on the information. To define the settings for signal parameters that are hard to predict, like the deactivation time of X coil, the activation time of Y coil and the noise level of contacts, etc., a probabilistic method may be a better choice.

### B. System Performance

The testing provided some valuable insight into the performance of the analysis system as well as the CBs that were tested. Table VIII shows test results for Westinghouse R3 CB created during the testing process.

Number	Open	Close
2	1	1
4	4	0
0	0	0
38	33	5
15	0	15
6	6	0
0	0	0
6	6	0
0	0	0
0	0	0
74 (34)	36	38
	Number           2           4           0           38           15           6           0           6           0           74 (34)	Number         Open           2         1           4         4           0         0           38         33           15         0           6         6           0         0           6         6           0         0           6         6           0         0           74 (34)         36

TABLE VIII TEMPORARY TEST RESULTS FOR ONE TYPE OF CB

The first noticeable thing in this table is that contact noise can be detected in 70% of the total test cases. This is due to the corrosion on the contacts, a common phenomenon in aged CBs. On the other hand, severe problems like slow CB are rare to encounter. Wrong classification is also detected during the testing process. As shown in Table VIII, 6 cases have been diagnosed with "Effect of Binding on Contact" and "Velocity Decreased". The fact is the "b" contact in 4 cases out of 6 has a bounce problem, and in 2 cases has excessive noise during the contact transition. But the system sees it as a transition delay problem, which incurs the firing of the "Velocity Decreased" and "Effect of Binding on Contact" rules. With a modification of both expert system rules and signal processing algorithm, the wrong classification is avoided.

The tests of the expert system also revealed several expert system decision-making sensitivities that need to be understood. The sensitivities are related to the input data and settings. It was assumed in the development of the knowledge base that the input data entered into the system is valid. In other words, all the signals are recorded correctly and there are no problems related to the connection of the recorder equipment. If invalid data is entered, then the system produces unpredictable results.

The expert system can only detect and classify problems that it was designed to analyze. If there are other abnormalities in the data, then the system will simply not recognize them. Additional development effort would be required for the system to be able to detect and classify new abnormalities.

The final tests showed that the system is able to accurately classify abnormalities present in the test data provided by CenterPoint Energy. The event report correctly identified the abnormalities and suggested the appropriate repair and maintenance information. The expert system also performed well with different variations of the same abnormality. For example, a dip in a signal can manifest itself in several different ways. In each case, the expert system was able to detect the abnormality. While the system performed well for test cases that were provided, more testing will be required in the future to determine the performance of the system for other CB types and CBs from other manufacturers.

# VII. CONCLUSION

This paper illustrates the following main features of the solution:

- CB operation can be monitored and analyzed in an automated way using advanced signal processing and expert system techniques.
- Signal processing has to be capable of extracting relevant features of the signals recorded from the CB control circuitry during CB operation.
- Expert system has to have sufficient facts and rules to be able to detect abnormalities in the CB operation based on the extracted signal features.
- By performing the automated analysis, two main goals are achieved: reduction in the time needed to detect an abnormality and consistency in performing the analysis.

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